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PHYSIOLOGICAL RESPONSES OF MEN AND WOMEN TO HUMID AND DRY HEAT.(U)
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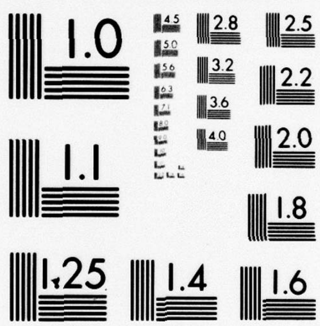

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) Physiological responses of men and women to humid and dry heat		5. TYPE OF REPORT & PERIOD COVERED
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Yair/Shapiro, Kent B./Pandolf, Barbara A./Avellini, Nancy A./Pimental ~~and~~ Ralph F./Goldman		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Research Institute of Environmental Medicine Natick, MA 01760		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS (16) 3E162777A845
11. CONTROLLING OFFICE NAME AND ADDRESS Same as 9. above		12. REPORT DATE (11) Nov~~ember~~ 1979
		13. NUMBER OF PAGES 26 pages (12) 29
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLAS
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

LEVEL II

16. DISTRIBUTION STATEMENT (of this Report)

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DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

sex-related differences; humid and dry heat; rectal temperature; heart rate; mean skin temperature; sweat loss; maximal oxygen uptake; body weight, skin surface area; body fat percentage; surface area-to-mass ratio; sweat suppression; thermoregulatory set point

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PHYSIOLOGICAL RESPONSES OF MEN AND WOMEN TO HUMID AND DRY HEAT

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Running Head: Heat Reactions of Men and Women

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Abstract

Sex-related differences were evaluated in 10 males and 9 females under hot-wet and hot-dry conditions. Preacclimatized subjects were exposed to a comfortable climate (20°C, 40% rh), mild-wet weather (32°C, 80% rh), two hot-wet conditions (35°C, 90% rh; 37°C, 80% rh) and two hot-dry conditions (49°C, 20% rh; 54°C, 10% rh). Exposures lasted 120 min: 10' rest, 50' walk ($1.34\ m \cdot s^{-1}$), 10' rest, 50' walk. During hot-dry exposures, heart rate (HR) and rectal temperature (T_{re}) were significantly lower for males than females by 13 and 20 $beats \cdot min^{-1}$ and by 0.25 and 0.32°C for the two conditions; no significant differences in sweat loss ($\dot{m}_{sw}$) were observed. During hot-wet exposures, both mean final T_{re} and $\dot{m}_{sw}$ were lower in females than males by 0.34 and 0.24°C and by 106 and 159 $g \cdot m^{-2} \cdot h^{-1}$, respectively (males sweated 25 and 40% more than females). None of these differences correlated with maximal oxygen uptake, body weight, skin surface area or percentage of body fat. During hot-wet exposures, a negative relationship between surface area-to-mass ratio (A_D/wt) and T_{re}, mean skin temperature, HR and change in heat storage was found. It was suggested that three major factors are involved in these differences: (a) higher A_D/wt for females than for males, (b) better sweat suppression from skin wettedness for women, and (c) higher thermoregulatory set point for women than for men.

Index terms: sex-related differences; humid and dry heat; rectal temperature; heart rate; mean skin temperature; sweat loss; maximal oxygen uptake; body weight; skin surface area; body fat percentage; surface area-to-mass ratio; sweat suppression; thermoregulatory set point

INTRODUCTION

The reactions of men to changes in environmental temperature have served as the basis for our understanding of human heat tolerance and thermoregulation. There appears to be less certainty about the thermoregulatory patterns of women, however. Physiological responses to heat stress may be expected to differ in men and women due to several possible factors, including the lower cardiorespiratory fitness (7,9,22), the higher body fat content (1,30), the lower body weight (27), the lower skin surface area and the higher surface area-to-mass ratio (A_D/wt) (12,24) of women compared to men. In addition, the fluctuating hormonal levels of estrogen and progesterone accompanying the menstrual cycle may also influence women's tolerance to heat stress (2,14,18).

Several studies have shown that women thermoregulate less effectively than men when exposed to an acute heat stress (3,6,26,31). Under the same heat load, core temperatures and heart rates were higher (3,13,15,26,31) and sweat rates were substantially lower (10,13,15,31) in women. However, when the cardiorespiratory fitness of the men and women was considered, physically fit women were found to have similar (7) or even lower (22,29) core temperatures and heart rates than fit men during an acute heat exposure despite their lower rates of sweating. Although heat acclimatization served to eliminate many of the sex-related physiological differences, sweat rates still remained lower for women (29,31).

One of the sources for the controversy in the literature regarding apparent sex-related thermoregulatory differences may result from the environmental conditions under which the experiment was conducted. Although little research has been performed comparing the responses of a group of men and women to both dry and humid climates, it appears that women may have a physiological advantage when tested under humid heat (20,29). In environments in which high rates of cooling by evaporation are not possible, the higher A_D/wt of women would allow both for more surface area for evaporative heat loss in relation to the heat produced by metabolism and for more heat loss via radiation and convection. The latter, however, is only true in environments in which ambient temperature is lower than skin temperature. In addition, the lower sweat rate of women should also prove advantageous under conditions in which the evaporative capacity of the environment is a limiting factor to evaporative cooling since less body fluids would be lost as sweat. Under dry conditions, when sweat output becomes increasingly important, the higher sweat rate of men may put them at an advantage over women.

If thermoregulatory function of the sexes is altered by climatic differences, the sex-related differences will have to be defined and explained separately for different climatic conditions. The purpose of this study, therefore, is to define the possible physiological differences between the sexes for humid and dry heat and to suggest the thermoregulatory mechanisms involved.

METHODS

Nine female and 10 male volunteer soldiers served as subjects. All subjects were totally informed with regard to experimental risk and gave their written informed consent. The physical characteristics of the females (mean $\pm$ SE) were: age, 22.0 $\pm$ 1.0 yr; height, 161.5 $\pm$ 2.3 cm; weight, 56.6 $\pm$ 2.6 kg; body fat, 29.6 $\pm$ 1.5% as determined by the method of Durnin and Womersley (11); body surface area, 1.59 $\pm$ 0.04 m^2; A_D/wt, 283.0 $\pm$ 5.7 $cm^2 \cdot kg^{-1}$; and maximal oxygen uptake ($\dot{V}O_2$ max), 40.5 $\pm$ 1.5 $ml \cdot kg^{-1} \cdot min^{-1}$ (range = 34.2 to 48.3) while the males were: age, 21.1 $\pm$ 0.6 yr; height, 178.6 $\pm$ 2.1 cm; weight, 75.6 $\pm$ 4.2 kg; body fat, 17.7 $\pm$ 1.6%; body surface area, 1.93 $\pm$ 0.06 m^2; A_D/wt, 258.9 $\pm$ 6.5 $cm^2 \cdot kg^{-1}$; and $\dot{V}O_2$ max, 52.3 $\pm$ 2.2 $ml \cdot kg^{-1} \cdot min^{-1}$ (range = 44.7 to 62.4). All experiments were conducted during early spring months.

Prior to the heat exposures, all subjects underwent medical examination, anthropometric measurements (height, weight, skinfold thickness) and determination of $\dot{V}O_2$ max. Maximal oxygen uptake was determined from an intermittent treadmill running test utilizing methods and techniques modified from Taylor et al. (28). During these tests, expired air was collected in Douglas bags; the volume was measured in a Collins Spirometer and converted to standard environmental conditions (STPD); and the O_2 and CO_2 concentrations were measured with an Applied Electrochemistry Model S-3A O_2 analyzer and Beckman LB-2 infrared CO_2 analyzer. Heart rate was calculated from R-R (ECG) intervals recorded on a Hewlett-Packard Model 1511A Electrocardiograph.

The nineteen male and female subjects, dressed in T-shirts, shorts, socks and indoor shoes, were then concurrently acclimatized for 6 consecutive days by walking on a level motor-driven treadmill at 1.34 $m \cdot s^{-1}$ for two 50-min periods with a preceeding and intervening 10-min rest period, at 49°C, 20% rh, 1 $m \cdot s^{-1}$ wind speed. After this acclimatization period, the subjects were exposed to six environmental variations: a comfortable (control) climate (T_a = 20°C, rh = 40%, P_a = 7.0 Torr, WBGT = 14.4°C), a mild-wet climate (T_a = 32°C, rh = 80%, P_a = 28.5 Torr, WBGT = 30.3°C), two hot-wet climates (T_a = 35°C, rh = 90%, P_a = 37.9 Torr, WBGT = 34.0°C; T_a = 37°C, rh = 80%, P_a = 37.7 Torr, WBGT = 34.5°C) and two hot-dry climates (T_a = 49°C, rh = 20%, P_a = 17.6 Torr, WBGT = 34.0°C; T_a = 54°C, rh = 10%, P_a = 11.3 Torr, WBGT = 34.2°C). Wind speed for all six climates was constant at 1 $m \cdot s^{-1}$. The WBGT was similar for the two hot-wet compared to the two hot-dry environments. Each of these six exposures lasted 120 min: 10' rest, 50' walk, 10' rest, 50' walk. Subjects walked at the same speed (1.34 $m \cdot s^{-1}$) on a level treadmill during these exposures as during acclimatization and were similarly dressed.

During all heat exposures, rectal temperature (T_{re}) was recorded from a Y.S.I. rectal thermistor probe inserted ~ 10 cm beyond the anal sphincter. Skin temperatures were monitored with a three-point thermocouple skin harness (chest, calf and forearm) and mean weighted skin temperature ($\bar{T}_{sk}$) was calculated according to Burton (5). Using a Hewlett Packard 9825A Calculator and 9862A Plotter on-line during experimentation, both $\bar{T}_{sk}$ and T_{re} were plotted for each subject at approximately 2-min intervals. Heat storage (ΔS) was calculated as follows: $\Delta S = 0.965\ (0.8\ \Delta\ T_{re} + 0.2\ \Delta\ \bar{T}_{sk})$ in $W \cdot kg^{-1}$. Heart rate was measured by radial artery palpation during the rest periods and after each 25 min of walking. Ad lib drinking was encouraged. Total body weight losses were determined from pre- and post-walk measurements on a K-120 Sauter precision electronic balance (accuracy of $\pm$ 10 g) for calculation of sweat rate. Sweat rate ($\dot{m}_{sw}$) was determined by loss of weight adjusted for water intake and urine output. Respiratory and metabolic weight losses were considered negligible and were not taken into account (16). At the end of the first rest period and at the end of each walking period, two-minute expired air samples were collected in Douglas bags and analyzed as previously described for calculation of metabolic rate. Criteria for terminating any heat exposure were a HR of 180 beats$\cdot$min^{-1} during exercise or of 140 beats$\cdot$min^{-1} during rest and/or a T_{re} above 39.5°C, dizziness, nausea, or dry skin.

Statistical Treatment.

Most variables were evaluated by use of a mixed design of two factors, with one factor being the two groups (male and female) and the other being the treatment (environmental conditions) which both groups received. When the subjects were separated by "degree of fitness" or other subgroup contrasts, a one-way analysis of variance was used to search for significant differences. In either design, if a significant F-value was found ($P < 0.05$), critical differences were analyzed by Tukey's procedure to locate the significant mean differences.

RESULTS

During heat acclimatization, mean final HR dropped 27 beats•min^{-1} in females and 30 beats•min^{-1} in males, final T_{re} dropped 0.46 and 0.70°C for males and females, respectively, and $\dot{m}_{sw}$ remained unchanged in both sexes. Although females maintained higher HR and T_{re} than males, both sexes showed similar trends in these parameters during acclimatization. More importantly, non-significant differences in physiological responses (HR and T_{re}) for both sexes during the last two acclimatization days (days 5 and 6) indicated a physiological acclimatization to the dry heat.

Figure 1 illustrates the mean changes in final T_{re} for males and females during the comfortable, mild-wet, hot-wet and hot-dry environments. No significant difference ($P > 0.05$) between the sexes was found for final T_{re} during the comfortable conditions (20°C, 40% rh). However, the T_{re} of males were higher than those of females for all wet conditions. This difference varied from 0.15°C in the mild-wet to 0.34°C in the 90% rh condition with the latter being statistically significant ($P < 0.05$). In contrast, under the hot-dry conditions, the final T_{re} of males was 0.25 and 0.32°C lower than females for the 49°C, 20% rh and 54°C, 10% rh environments, respectively. The difference between the sexes at 54°C, 10% rh was statistically significant ($P < 0.05$). When the environmental conditions were compared according to equal WBGT, the females were found to have the same final T_{re} value for 35°C, 90% rh and 49°C, 20% rh (WBGT ≃ 34°C) as well as for the 37°C, 80% rh and 54°C, 10% rh conditions (WBGT ≃ 34.5°C). The males, however, displayed significantly higher final T_{re} values for the wet conditions of these corresponding climatic (WBGT) contrasts.

FIGURE 1

As seen in Table 1, the final mean observations of $\bar{T}_{sk}$ for the men and women for the various climatic conditions were similar in trend to the corresponding T_{re}

responses. The $\bar{T}_{sk}$ for the females was higher in the hot-dry conditions but lower than the males in the hot-wet conditions. The differences between the sexes were statistically significant for the 32°C, 80% rh and 54°C, 10% rh climates with a full degree centigrade difference between the sexes for the latter condition (see Table 1).

TABLE 1

The analysis of group heat storage comparisons utilized the difference between the initial and final heat storage values (Δ heat storage in Watt$\cdot$kg^{-1}) each hour. Obviously, the change in heat storage (ΔS) reflected alterations in $\bar{T}_{sk}$ and T_{re} with time. Since females exhibited smaller changes in T_{re} and $\bar{T}_{sk}$ than males during the hot-wet conditions, they subsequently demonstrated less change in S during the first hour as seen in Figure 2. Similarly, the larger increases in T_{re} and $\bar{T}_{sk}$ for the females in the hot-dry climates were reflected in their larger ΔS values for the first hour of exposure. The only significant differences between the men and women, however, were for the 35°C, 90% rh and 54°C, 10% rh environments ($P < 0.06$, see Table 1). During the second hour, under the dry conditions, the ΔS were negligible (0.015 and 0.099 W$\cdot$kg^{-1} for the males and 0.078 and 0.089 W$\cdot$kg^{-1} for the females). Under the hot-wet environments, the second hour ΔS were 30-50% of the corresponding first hour values.

FIGURE 2

As expected, no sex-related differences were found for metabolic rate in either the dry or wet conditions. These climatic contrast values are presented in Table 1.

The sex-related differences for final mean HR responses for the various climatic conditions are presented in Figure 3. Similar HR responses were observed for both sexes during the control condition and during the hot-wet conditions.

Although the responses of the males were slightly higher for the wet conditions, these differences were not significant. In the dry heat, however, there was a significant difference ($P < 0.05$) in the HR response, with the males averaging 13 and 20 beats$\cdot$min^{-1} lower than the females (see Table 1).

FIGURE 3

Sweat rate responses for the various environmental conditions are presented in Figure 4. Similar $\dot{m}_{sw}$ ($g \cdot m^{-2} \cdot h^{-1}$) were observed in the control condition for both sexes. In the hot-wet conditions males were found to sweat more than females. In the most severe humid climate (37°, 80% rh), males sweated 40% more than females (560 and 401 $g \cdot m^{-2} \cdot h^{-1}$, respectively), with the difference being highly significant ($P < 0.01$). In the other two wet conditions (32°C, 80% rh and 35%, 90% rh), males had a 23% greater sweat output than females over the 2-hour exposure. This difference was only significant ($P < 0.01$) for the latter condition, however, (see Table 1). Although males demonstrated a higher sweat rate than females in the dry conditions, these differences were not statistically significant (see Table 1). When the sweat loss was expressed in $g \cdot kg^{-1} \cdot h^{-1}$ rather than in $g \cdot m^{-2} \cdot h^{-1}$, the same sex-related observations were seen for the control condition and wet climates, as seen in Table 1. In the dry climates, however, the females were seen to sweat more per unit weight than the males but not significantly so.

FIGURE 4

No significant differences in water consumption or state of hydration were found between sexes in the control or the mild-wet conditions (Table 1). In the other four conditions (hot-wet and hot-dry), the females drank proportionately more than the males (10-37% more when calculated as a percentage of lean body mass). However, these were not statistically significant differences. Although no statistically significant differences in the sex-related state of hydration were observed for these climatic conditions, the females were found to be less dehydrated than the males in the hot-wet climates (30-47% less) as shown in Table 1.

Each sex was divided into two subgroups (a high group and a low group) according to the following five parameters: $\dot{V}O_2$ max, body weight, surface area, percentage of body fat, and surface area-to-mass ratio (A_D/wt). Each subgroup was arranged in such a manner so that comparisons could be made of similar male and female subgroups for each parameter. For example, the five less physically fit males had similar $\dot{V}O_2$ max compared to the five more fit females ($P > 0.05$).

When the thermoregulatory responses of the subjects in various climates were correlated with each of these five parameters, no significant relationships were found with physical fitness (Table 2), body weight, surface area, or percentage body fat. There was, however, some correlation between physiological responses and A_D/wt. When the male and female subgroups were matched for A_D/wt no differences were found for final T_{re}, $\bar{T}_{sk}$, ΔS and HR in the hot-wet climates, as seen in Table 3. The $\dot{m}_{sw}$, however, was still higher for the males than for the females (11.19 $g \cdot kg^{-1} \cdot h^{-1}$ for females and 14.61 for males). In the hot-dry conditions, these same subgroups differed from each other in the thermoregulatory responses. No further correlation was found for thermoregulatory responses between the different phases of the menstrual cycle or between the natural cycle and the artificial one (contraceptive), either in humid or dry environments.

TABLE 2

TABLE 3

DISCUSSION

The major objective of this study was to determine whether sex-related differences in thermoregulation exist; and if so, whether there was any method to define these differences. A major methodological problem of the study was the inability to find groups of males and females matched in all their physical characteristics, namely: body weight, skin surface area, percentage of body fat and cardiorespiratory physical fitness. This problem was partially solved by dividing each sex into two subgroups and matching the subgroups as "small" males vs. "big" females, or more fit females vs. less fit males.

The sex-related differences concluded from this investigation are summarized in Table 4. In comfortable climatic conditions (20°C, 40% rh) men and women reacted in a physiologically similar fashion. Under wet conditions, whether mild or hot, females tolerated the heat better than males. They displayed lower deep body and skin temperatures, and therefore lower heat storage, while demonstrating lower sweat rates and subsequently less dehydration than males. In contrast, under hot-dry conditions, males seemed to be at a physiological advantage. Compared to females, they showed lower deep body and skin temperatures, lower HR, lower ΔS, – HEAT STORAGE and similar sweat rates.

TABLE 4

Thus, there appear to be sex-related differences in thermoregulation but the physiological advantage seems to be related to the type of climate, particularly whether the environment is wet or dry. Sex-related differences in thermoregulation suggest to some the importance of the sex hormones as a primary mechanism. We suggest from the present findings that the sex hormone influence in thermoregulation can be excluded as a critical factor for several reasons. First, in explaining male-female differences in thermoregulation the hormonal level should not react preferentially to hot-dry or hot-wet climates, but should show a similar response to increased environmental heat, which it did not in this study. Secondly, no effect of the menstrual phase appeared evident in our group of females when they were divided into two subgroups: those exposed to the different climatic conditions before, and those exposed, after ovulation. In addition, the women who were taking oral contraceptive (n=4) showed the same responses to the changing environments as the other women. This lack of effect of menstrual stage on heat tolerance is in agreement with the findings of others (12,14,16,25).

Differences in the physical characteristics of men and women are also thought to be important factors to be considered in making comparisons between the sexes. As expected, the women in this study were shorter, lighter, fatter and less physically fit than the men. Thus, each of these factors could be thought of as a possible cause in sex-related thermoregulatory differences. However, analysis according to matched subgroups yielded no relationship between the climatic differences observed and the physical characteristics of the sexes. Thus, women cannot be defined as "smaller, fatter, less fit men" for thermoregulatory purposes.

Only one anthropometric factor, the surface area-to-mass ratio (A_D/wt), was found to be related to the specific physiological adjustments to the various climates (wet and dry). As expected (21), this ratio was 10% higher for the females than for the males. Comparison of the five women with the lower A_D/wt to the five men with the higher A_D/wt (Table 3) yielded two subgroups with similar A_D/wt. Further comparison of these two subgroups showed a similarity in mean final T_{re}, $\bar{T}_{sk}$, ΔS and HR during exposure to hot-wet conditions, but the males sweated 30% more. These observations can be explained in part by two different mechanisms. First, a higher A_D/wt is an advantage in humid climates. Heat production is mainly weight-dependent, while heat dissipation is related to the skin surface area. In hot-wet environments, one cannot evaporate necessary requirements; therefore, the more surface area available in relation to the heat produced, the greater the cooling power (24). Secondly, since a high sweat rate would be ineffectual in climates that do not allow for adequate evaporation, the body can conserve its water by suppression of the non-evaporative sweat loss. The women, who demonstrated lower sweat rates during exposure to the wet climates, were therefore at an advantage since they became less dehydrated than the men while working in the heat (Table 1). Although the reason for the often documented lower sweat rates of women in humid conditions is not clearly defined, it may be attributable to the more rapid development of hidromeiosis (4,29), or suppression of sweating, which is related to skin wettedness (4). Females may have a better and more efficient feedback from skin wettedness than males which thus suppresses the nonevaporative sweat loss in humid heat.

In hot-dry environments, the former mechanisms do not function in the same fashion. The sweat suppression mechanism is irrelevant in hot-dry climates because the skin is almost dry. In dry environments, higher sweat production results in higher cooling power. The above can explain the similarity in sweat loss for both sexes in dry climates. In dry conditions, a high A_D/wt can be a disadvantage because it allows rapid forced heat gain by convection and radiation (12,24). In this case, a high A_D/wt works in two different directions and results in more evaporative cooling power on the one hand, and more heat gain from the environment on the other hand. Within the sexes a small advantage, if any, was found in having a higher A_D/wt in dry climates, but not of the magnitude as in humid environments. No similarity between subgroups of the sexes was found in the dry climatic exposures; thus the importance of A_D/wt in dry climates is very small.

We suggest that the differences in the dry environments can be explained in large part by different thermoregulatory set points for the sexes; higher for the women than for the men. This hypothesis can be supported by the evidence that during the second hour of the dry-climatic exposures both sexes were under thermal equilibrium, with negligible heat storage. The higher thermoequilibrium of the females is most probably the result of a higher thermoregulatory set point. Sweating would thus be initiated at a higher core temperature (2,13) and more heat storage would occur as was the case in the 54°C, 10% rh environment (Table 1). In support of this contention, Roberts et al. (23) showed sweating onset in terms of lower esophageal temperature to be reduced for males as compared to females (0.2°C difference pre-training, pre-acclimation; 0.3°C post training; and 0.4°C post acclimation).

It can be concluded that females and males react in a physiologically similar manner under comfortable environmental conditions, females tolerate hot-wet climates better than males, and males better tolerate hot-dry conditions. A possible explanation for these differences involves three considerations. The higher A_D/wt for females may be a morphological advantage in hot-wet climates, and a disadvantage in hot-dry environments. Females seem to have better peripheral feedback from skin wettedness, which suppresses nonefficient sweating in humid conditions. Females also appear to have a higher central thermoregulatory set point than males, and therefore are more intolerant of hot-dry environments as compared to males.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance of Ms. Ella H. Munro in the statistical analysis of the data, and Ms. Elaine Lampert for her technical assistance in preparing the manuscript.

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TABLE 1. Sex differences in the various climatic conditions (mean and S E) for males (M) and females (F)

	CONTROL		MILD-WET		HOT-WET				HOT-DRY			
T_a °C, rh %	20°C, 40%		32°, 80%		35°, 90%		37°, 80%		49°, 20%		54°, 10%	
	M	F	M	F	M	F	M	F	M	F	M	F
Final T_{re} °C	37.53 .07	37.60 .08	37.82 .08	37.67 .04	38.52 .11	38.18* .07	38.73 .09	38.49 .07	37.94 .08	38.19 .07	38.12 .09	38.44* .10
Final HR beats·min^{-1}	85.9 2.6	85.2 3.0	105.1 2.4	102.4 2.7	138.7 4.7	136.8 3.2	148.8 3.8	143.0 3.0	117.0 3.4	130.1* 4.6	127.3 5.1	147.9* 1.6
Final $\bar{T}_{sk}$ °C	31.02 .33	30.49 .40	34.13 .15	33.43* .13	36.17 .09	35.77 .10	36.51 .08	36.30 .11	35.80 .20	36.23 .29	36.29 .17	37.30* .14
Metabolism ml·kg^{-1}·min^{-1}	14.34 .46	13.93 .29	14.66 .40	13.85 .37	15.25 .53	14.74 .28	14.74 .62	14.38 .33	14.42 .39	14.35 .31	14.64 .38	14.39 .34
ΔS - 1st hour watt·kg^{-1}	.112 .074	.055 .051	.381 .064	.219 .042	.978 .067	.697** .081	.949 .070	.751 .048	.560 .055	.569 .062	.619 .060	.900* .097
$\dot{M}_{sw}$ g·kg^{-1}·h^{-1}	2.34 .26	2.33 .24	7.52 .32	6.70 .31	14.27 1.03	12.65 .63	14.46 .66	11.32* .88	12.98 .58	13.08 .50	15.11 .54	16.49 .77
$\dot{M}_{sw}$ g·m^{-2}·h^{-1}	92 12	84 10	293 16	238 14	554 41	448* 22	560 26	401* 30	502 19	462 15	586 23	582 24
Dehydration % of LBM	.225 .079	.222 .094	.550 .160	.632 .218	1.412 .207	.990 .229	1.136 .202	.607 .282	1.303 .148	1.197 .200	1.178 .256	1.152 .236
H_2O Consumption % of LBM	.35 .11	.45 .07	1.29 .25	1.29 .25	2.06 .21	2.63 .28	2.38 .21	2.62 .17	1.85 .15	2.53 .25	2.50 .22	3.21 .24

* $p < 0.05$

** almost significant at 5% level - the critical difference needed for 5% is 0.286, the actual difference is 0.281.

TABLE 2. Cardiovascular physical fitness and thermoregulation

		MALES		FEMALES	
		MORE FIT	LESS FIT	MORE FIT	LESS FIT
	No. of Subjects	5	5	5	4
	$\dot{V}O_2$ max $ml \cdot kg^{-1} \cdot min^{-1}$	58.3 ± 1.7*	46.3 ± 0.6	43.7 ± 1.3	36.6 ± 1.1
HOT-DRY	T_{re}, °C	37.92 ± 0.13	37.96 ± 0.12	38.22 ± 0.06	38.16 ± 0.14
	$\bar{T}_{sk}$, °C	35.82 ± 0.16	35.78 ± 0.39	36.40 ± 0.36	36.02 ± 0.53
	ΔS, $W \cdot kg^{-1}$ (1st h)	0.572 ± 0.063	0.549 ± 0.097	0.623 ± 0.064	0.501 ± 0.115
49°C, 20%	HR, $beats \cdot min^{-1}$	113 ± 6.0	121 ± 3.1	125 ± 4.4	137 ± 8.2
	$\dot{M}_{sw}$, $g \cdot kg^{-1} \cdot h^{-1}$	13.33 ± 0.77	12.63 ± 0.92	13.28 ± 0.41	12.83 ± 1.08
HOT-WET	T_{re}, °C	38.69 ± 0.15	38.77 ± 0.11	38.48 ± 0.07	38.50 ± 0.14
	$\bar{T}_{sk}$, °C	36.50 ± 0.13	36.52 ± 0.12	36.24 ± 0.11	36.38 ± 0.23
	ΔS, $W \cdot kg^{-1}$ (1st h)	0.924 ± 0.124	0.975 ± 0.080	0.709 ± 0.050	0.804 ± 0.090
37°C, 80%	HR, $beats \cdot min^{-1}$	144 ± 6.5	154 ± 3.2	140 ± 4.6	146 ± 3.3
	$\dot{M}_{sw}$, $g \cdot kg^{-1} \cdot h^{-1}$	15.41 ± 1.02	13.50 ± 0.66	11.65 ± 0.81	10.92 ± 1.84

*Mean ± S E

TABLE 3. Surface area-to-mass ratio (A_D/wt) and thermoregulation

		FEMALES		MALES	
		Higher A_D/wt	Lower A_D/wt	Higher A_D/wt	Lower A_D/wt
	No. of Subjects	4	5	5	5
A_D/wt	($cm^2 \cdot kg^{-1}$)	297 ± 5*	272 ± 6	273 ± 5	244 ± 7
	T_{re}, °C	38.10 ± 0.11	38.27 ± 0.08	37.85 ± 0.11	38.02 ± 0.12
HOT-DRY	$\bar{T}_{sk}$, °C	36.30 ± 0.30	36.18 ± 0.50	35.96 ± 0.09	35.64 ± 0.39
	ΔS, $W \cdot kg^{-1}$(1st h)	0.486 ± 0.076	0.635 ± 0.089	0.589 ± 0.055	0.531 ± 0.100
49°C, 20%	HR, $beats \cdot min^{-1}$	131 ± 9.7	130 ± 4.2	116 ± 5.5	118 ± 4.6
	$\dot{M}_{sw}$, $g \cdot kg^{-1} \cdot h^{-1}$	13.83 ± 0.76	12.47 ± 0.57	13.38 ± 0.77	12.59 ± 0.91
	T_{re}, °C	38.35 ± 0.05	38.60 ± 0.09	38.62 ± 0.13	38.84 ± 0.11
HOT-WET	$\bar{T}_{sk}$, °C	36.15 ± 0.17	36.44 ± 0.15	36.40 ± 0.10	36.62 ± 0.11
	ΔS, $W \cdot kg^{-1}$(1st h)	0.686 ± 0.022	0.804 ± 0.081	0.834 ± 0.115	1.065 ± 0.046
37°C, 80%	HR, $beats \cdot min^{-1}$	140 ± 4.1	145 ± 4.3	147 ± 7.8	151 ± 1.5
	$\dot{M}_{sw}$, $g \cdot kg^{-1} \cdot h^{-1}$	11.49 ± 1.79	11.19 ± 0.91	14.61 ± 1.04	14.30 ± 0.91

*Mean ± S E

TABLE 4. Summary of sex-related trends in thermoregulatory responses to various climates

	COMFORT	MILD-WET	HOT-WET	HOT-DRY
T_{re}	=	↓	↓	↑
HR	=	=	=	↑
$\bar{T}_{sk}$	=	↓	↓	↑
ΔS	=	↓	↓	= or ↑
$\dot{M}_{sw}$	=	↓	↓	=
Dehydration	=	=	↓	=
H_2O Consumption	=	=	↑	↑

= No difference

↓ Females are lower than males

↑ Females are higher than males

FIGURE LEGENDS

FIG. 1. Comparison of mean final rectal temperature (T_{re}) between males (M) and females (F) in a control-comfortable climate (20°C, 40% rh), humid climates (32°C, 80% rh; 35°C, 90% rh; 37°C, 80% rh) and dry climates (49°C, 20% rh; 54°C, 10% rh).

FIG. 2. Comparison of 1st-hour mean heat storage (ΔS - $W \cdot kg^{-1}$) between males (M) and females (F) in the comfortable climate, the three humid climates and two dry climates.

FIG. 3. Comparison of mean final heart rate (HR) between males (M) and females (F) in the control-comfortable climate, the three humid climates and the two dry climates.

FIG. 4. Comparison of mean hourly sweat rate ($\dot{m}_{sw}$ - $g \cdot m^{-2} \cdot hr^{-1}$) between males (M) and females (F) in the comfortable climate, the three humid climates and the two dry climates.

1. *The views, opinions, and/or findings contained in this report are those of the* author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other official documentation.

2. Human subjects participated in these studies after giving their free and informed voluntary consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

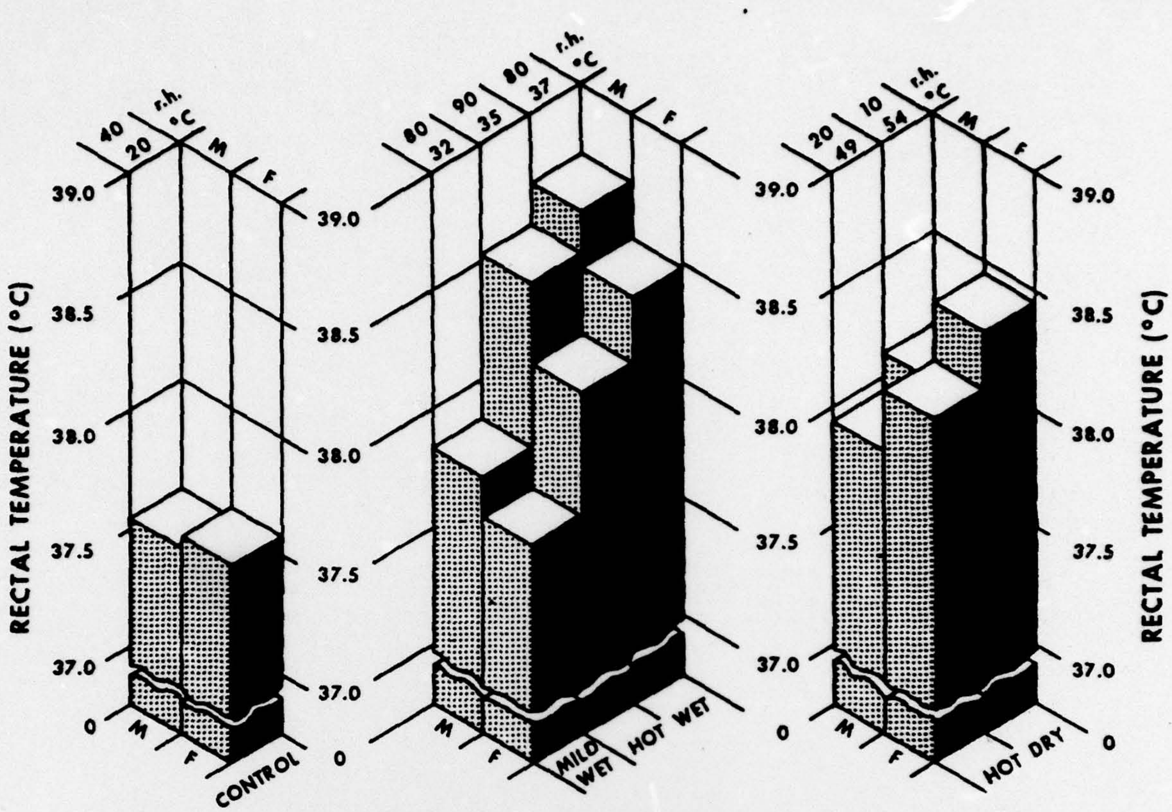
RECTAL TEMPERATURE (°C)
39.0
38.5
38.0
37.5
37.0
0
40
20
r.h.
°C
M
F
CONTROL
80
32
90
35
80
37
MILD WET
HOT WET
20
49
10
54
HOT DRY

FIG. 1

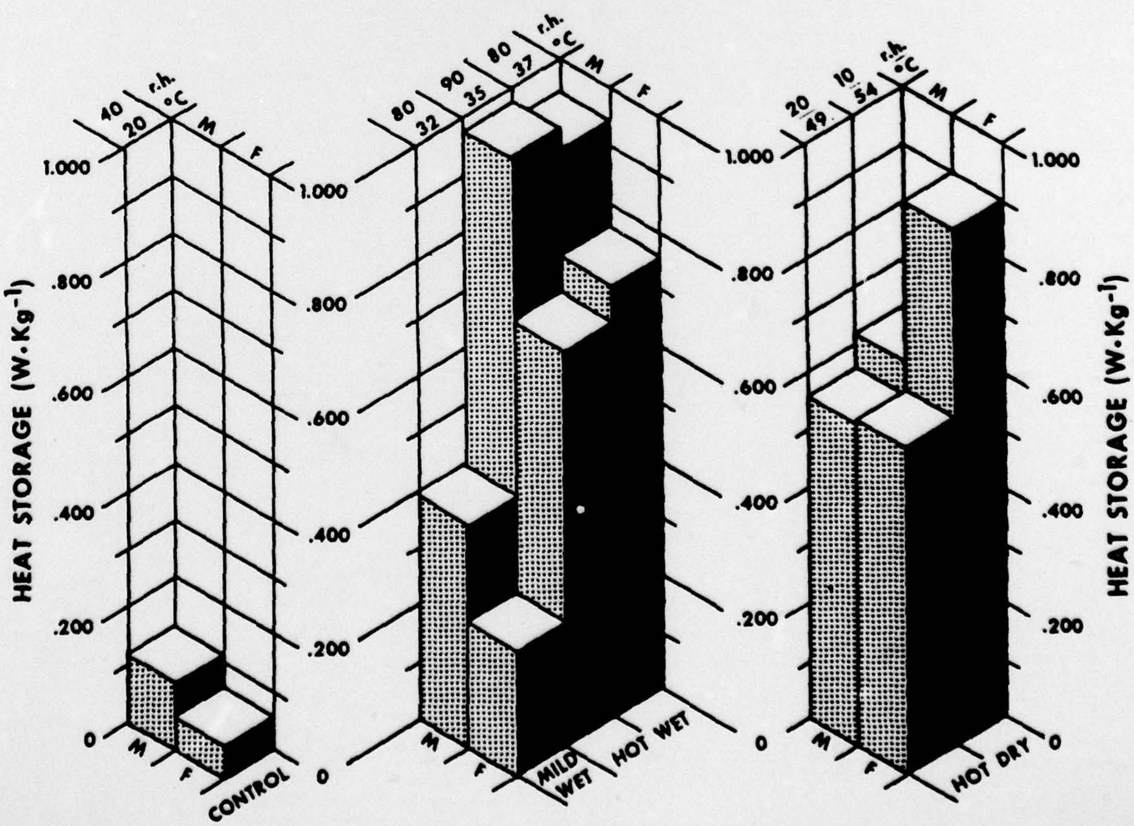
HEAT STORAGE (W·Kg^{-1})
1.000
.800
.600
.400
.200
0
40
20
r.h.
°C
M
F
CONTROL
80
32
90
35
80
37
MILD WET
HOT WET
20
49
10
54
HOT DRY

FIG. 2

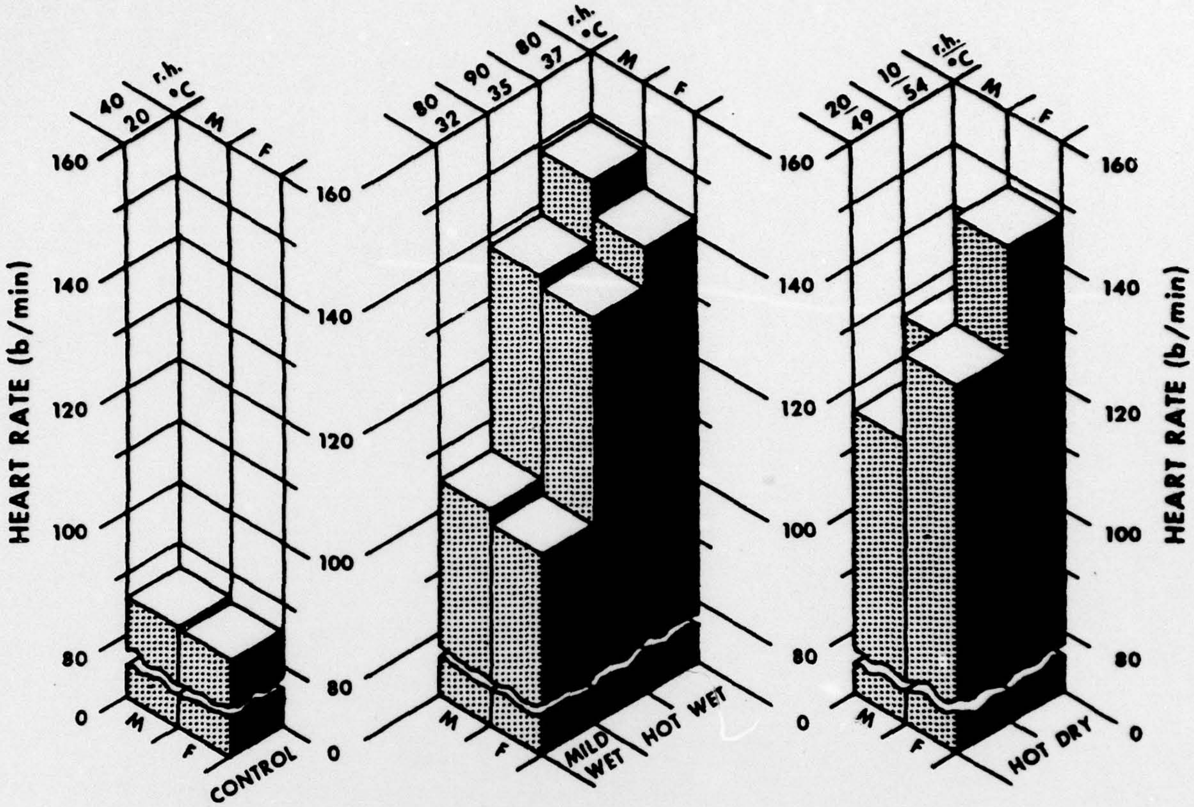
HEART RATE (b/min)
r.h.
°C
40
20
80
32
90
35
80
37
20
49
10
54
M
F
CONTROL
MILD WET
HOT WET
HOT DRY
0
80
100
120
140
160

FIG. 3

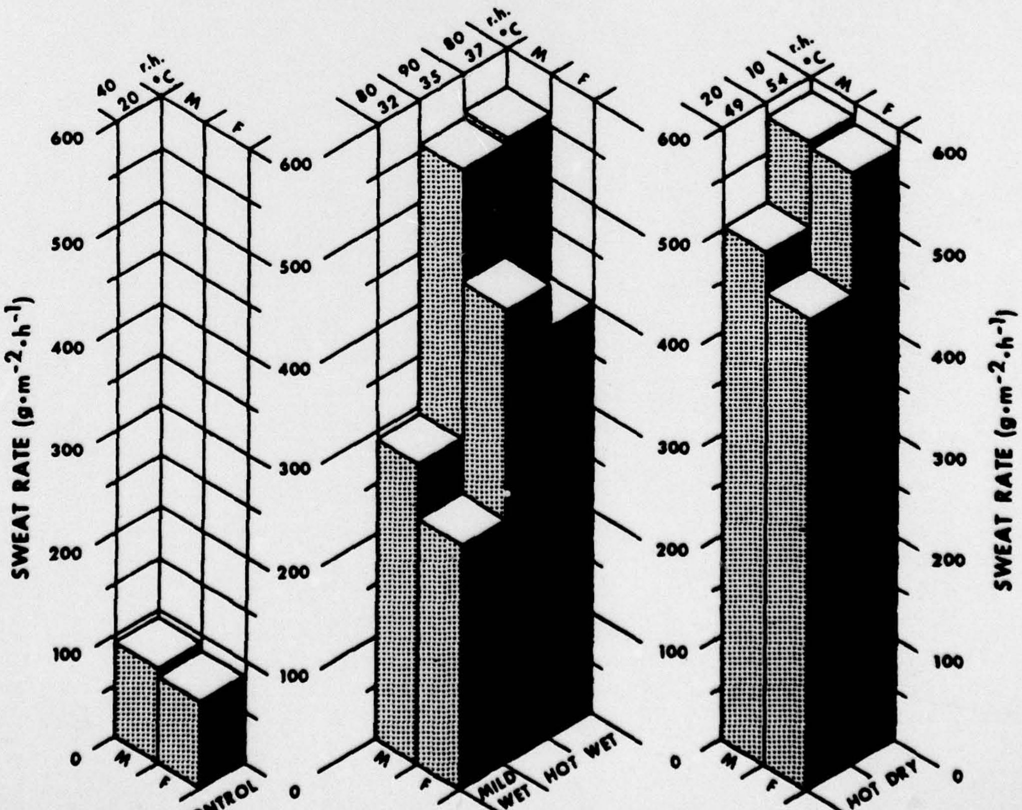
SWEAT RATE (g·m-2·h-1)
r.h.
°C
40
20
80
32
90
35
80
37
20
49
10
54
M
F
CONTROL
MILD WET
HOT WET
HOT DRY
0
100
200
300
400
500
600

FIG. 4